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Visual-vestibular interactions and spatial (dis)orientation in flight and flight simulation

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Visual-vestibular interactions and spatial (dis)orientation in flight and flight simulation

J.E. Bos, R.J.A.W. Hosman, and W. Bles

SUMMARY

Purpose: To optimise moving base simulators, we here present and analyse a model describing human motion and attitude perception based on visual and vestibular inputs. With such a model, insight can be obtained regarding differences between perception of real and simulated aircraft motion. The use of this model is demonstrated by focussing on the simulation of a take-off. For moderate accelerations we considered the Stewart platform and a fixed base simulator. With a Stewart platform, surge and tilt are combined to approximate a continuous forward linear acceleration. Due to simulator motion limits, and the fact that tilt must not be felt, this approximation is incomplete. For high accelerations centrifugation is used instead. Then, however, concomitant angular information may ruin the desired effect of only a forward linear acceleration. The question always is how then to optimise simulator performance.

Methods: The model used is elaborated first. The key issue regarding the processing of vestibular cues concerns the way accelerations due to motion are separated from those by gravity. Here we take a simple low-pass filter operating in an earth fixed frame of reference to solve this problem. The transformation of otolith signals representing specific force is driven by canal signals representing angular velocity. We separate visual information in circular and linear flow-information, and in frame information. The circular optic flow is just added to vestibular canal signals. Linear optic flow is weighted with high-pass filtered otolith afferents. Visual frame information is weighted with vestibular and longitudinal body-axis information (idiotropic vector). To evaluate this model, we secondly simulated a simulator take-off experiment with a moderate acceleration as performed by Groen et al. (2001), whose data revealed motion filter parameters for a run that was judged to be good, and one that was judged to be bad. For high acceleration take-offs we analysed the centrifuge simulation applying the centripetal acceleration. All model simulations were run with and without concomitant visual information such as to elucidate the effects of vision, which is relevant for flying under bad or no visibility conditions.

Results: First, we were able to build a model that does give quantitative predictions of linear acceleration and velocity, angular velocity and attitude perceptions. Second, both Stewart platform, fixed base, and centrifuge perception data were reproduced satisfactory by the model.

Conclusions: We here conclude that: 1) The presented theory on motion and attitude perception is applicable in optimising motion filters. 2) Linear velocity and acceleration, angular velocity, and attitude perception may all behave differently because of different visual-vestibular interactions, and these all proved to be high value factors in judging the quality of a simulator manoeuvre. 3) A good simulator run is characterised by a minimal difference between the four mentioned perception components in the simulator and in real. A reversed acceleration perception should be prevented anyway. 4) Angular velocity is the most annoying factor in flight simulation. 5) With impeded vision the physical motion is important, and simulator runs are inadequate then. 6) Physical motion adds essential elements to motion and attitude perception that cannot be realised by visual cues only.

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Visueel-vestibulaire interacties en ruimtelijke (des)oriëntatie in vlucht en vliegsimulatie

J.E. Bos, R.J.A.W. Hosman en W. Bles

SAMENVATTING

Vraagstelling: Om bewegende simulatoren te optimaliseren, presenteren en analyseren we hier een model dat de bewegings- en standperceptie van mensen beschrijft, gebaseerd op visuele en vestibulaire prikkels. Met zo'n model kan inzicht verkregen worden in de verschillen tussen de waarneming van echte en gesimuleerde vliegtuigbewegingen. Het nut van dit model blijkt uit wat er gebeurt bij de start van een vliegtuig. Voor matige versnellingen hebben we een Stewart platform en een stilstaande simulator bekeken. Een voorwaartse lineaire en een opwaartse kantelbeweging worden bij het Stewart platform gecombineerd om een continue voorwaartse lineaire versnelling te simuleren. Door de beperkte bewegingsenveloppe van de simulator, en doordat de kanteling niet gevoeld mag worden is deze benadering niet perfect. Voor hoge versnellingen worden ook wel centrifuges gebruikt. Maar dan kan de centrifuge-rotatie weer het gewenste effect van enkel een voorwaartse versnelling versjteren. De vraag hierbij is steeds hoe je dan toch de simulator prestaties kunt optimaliseren.

Werkwijze: Eerst leiden we het model af. De hamvraag hierbij is hoe het onderscheid gemaakt kan worden tussen vestibulair waargenomen versnellingen ten gevolge van beweging en de valversnelling. Hierbij nemen we aan dat dit probleem opgelost kan worden met een eenvoudig laagdoorlaatfilter in een aardvast referentiekader. De transformatie van otolietsignalen die de specifieke kracht weergeven wordt gestuurd door kanaalsignalen die hoeksnelheid weergeven. Wat betreft de visuele informatie maken we vervolgens onderscheid tussen draai- en lineaire stromingsinformatie en in kader-informatie. Visueel waargenomen draaibewegingen worden eenvoudigweg opgeteld bij de kanaalsignalen. Visueel bepaalde lineaire snelheid wordt gewogen met hoogdoorlaat gefilterde otolietsignalen. Het visuele kader wordt gewogen met vestibulaire en longitudinale lichaamsas-informatie (idiotropische vector). Ter evaluatie van dit model hebben we vervolgens een simulatorexperiment van Groen et al. (2001) gesimuleerd, waarbij een start met een matige versnelling is gebruikt. Deze data gaven aan welke parameters resulteerden in een als goed beoordeelde run en welke in een als slecht beoordeelde run. Voor een hoge versnellingsstart hebben we gekeken naar de simulatie met een centrifuge waarbij de centripetale versnelling wordt benut. Alle modelsimulaties zijn uitgevoerd met en zonder visuele informatie om het effect van zicht duidelijk te maken, en dat is relevant voor het vliegen onder slechte of geen zicht condities.

Resultaten: Eerst is het gelukt om een model samen te stellen dat kwantitatieve voorspellingen geeft van de waargenomen lineaire versnelling en snelheid, hoeksnelheid en stand (t.o.v. de aardverticaal). Daarna bleek dat we de Stewart platform, stilstaande simulator en centrifuge-data uit de literatuur naar tevredenheid konden reproduceren.

Conclusie: We concluderen hier dat: 1) De gegeven theorie van bewegings- en standsperceptie toepasbaar is bij het optimaliseren van bewegingsfilters. 2) Perceptie van lineaire snelheid en versnelling, hoeksnelheid en stand kunnen verschillen door verschillen in visueel-vestibulaire interacties, en het zijn allemaal belangrijke niet te verwaarlozen factoren bij de beoordeling van simulator manoeuvres. 3) Een goede simulator-run wordt gekarakteriseerd door een minimaal verschil tussen de vier genoemde perceptie-componenten in de simulatie en in het echt. Een tegengestelde versnellingswaarneming dient hierbij sowieso vermeden te worden. 4) Rotatie is de meest hinderlijke factor in vliegsimulatie. 5) Bij slecht zicht is fysieke beweging belangrijk, en simulaties daarvan zijn dan niet toerijkend. 6) Fysieke beweging voegt essentiële informatie toe aan bewegings- en standsperceptie die niet met enkel visuele stimulatie gerealiseerd kan worden.

1   INTRODUCTION

In flying an aircraft, a pilot's motion and attitude perception and his control behaviour is dependent upon the feedback of visual and vestibular stimulation due to the aircraft motions. When using moving base simulators for training purposes, this is even more true, because subtle differences in motion perception between real and simulated aircraft motion may give rise to errors in controlling the true aeroplane. To understand the differences in perception between true and simulated motion and for possible optimisation of the algorithms driving these simulators, knowledge of the human spatial orientation system is helpful. Because progress in the field of spatial orientation and motion perception research now is to a point where application in the field of vehicle simulation comes close, we will here present a comprehensive perception model describing these visual-vestibular interactions. As a result we will show that there are considerable differences in the perception of real and simulated motion indeed. The manoeuvre considered here as an example is that of a take-off. We will consider one with a moderate acceleration as simulated by means of a Stewart platform and a fixed base simulator (relevant for civil aviation), and another with a high acceleration as simulated by means of a centrifuge (relevant for military aviation).

For moving-base flight simulation the aircraft motions have to be changed to simulator motions by a motion cueing algorithm (the motion filter) due to the limited motion freedom of simulator motion systems. It may therefore be anticipated that there are also differences between the perception of real and simulated aircraft motion. One way to gain insight in these differences is by systematic observation of the different perceptions by varying parameter settings (e.g. Groen et al., 2001). Another is by using knowledge of visual-vestibular interactions put into a model of motion and attitude perception (e.g. Telban et al., 1999; Telban & Cardullo, 2001; Bos et al., 2001). The latter offers the advantage of unravelling spatial orientation into separate compo-nents like acceleration, velocity, and position, and make the differences between real and simulated motion perception explicit. It furthermore offers the advantage for optimising motion filters by minimising the predicted perception differences of real and simulated motion. Up to now, the adjustment of motion cueing algorithms is set for particular simulations, and is more an empirical art based on the experience of the simulation engineer and the subjective judgement of simulator acceptance pilots. Lastly, validation of a model does only require a limited number of validations (equal to the number of parameters controlling the model), whereupon predictions can be made for any type of motion.

The development of the model for human motion perception we previously introduced was inspired by our attempts to set up a model to predict motion sickness (Bos & Bles, 1998, 2001). The relationship between motion perception and motion sickness results from the assumption that motion sickness is the outcome of a discrepancy between the gravitational vertical as determined by integrated sensory information and a vertical as expected based on previous experience (Bles et al., 1998, 2000). This relationship will be explicated here first, also to put the question under consideration within a broader view. To this end, Fig. 1 shows the observer model of Bos & Bles (2001) which describes the control of body motion. Here, a desired body state ($\mathbf{u}_d$) directs a controller (C) generating motor commands ($\mathbf{m}$) that subsequently drive the muscles in our body to fulfil the desire. Together with external perturbations (**ext**, by a car, ship

or aeroplane e.g.), this results in the actual body state (**u**). This state is sensed by visual, vestibular (inner ear labyrinth), somatosensory (surface and subsurface force and deflection sensors), and to some degree also by auditory sensors, all confined in the block S of Figure 1. After some central nervous system (CNS) processing and delay, this results in signals representing the state of the body (**u**$_s$). Parallel to this primary path of signal flow, akin signals are supposed to be generated by a copy of the primary path ($\hat{B}$ and $\hat{S}$), together called an internal model or neural store which is supposed to be created by previous experiences. The input of this internal model is a copy of the motor commands (also called an efference copy). Here the output **û** should be a better estimate of the body state as compared to the output **u**$_s$, and it is this estimate that is compared with the desired state **u**$_d$ to generate the error signal (**e**). Optimally, the output of the internal model **û**$_s$ should be equal to that of the primary path **u**$_s$. If, for example, an external perturbation is present, these signals will not be equal. The difference or conflict **c** = **u**$_s$ - **û**$_s$ may then give rise to an additional feedback signal, weighted by K, and used by the internal model to drive the difference towards zero. In terms of Kalman filtering, this conflict (**c**) is also called the "innovation". Now the body state **u** has several components, e.g. angular velocity (**ω**), linear acceleration (**a**), and gravity (**g**). Oman (1982) suggested that the resulting multi-vectorial conflict (**c**) is correlated with motion sickness (**s**) as conceptually postulated by Reason & Brand (1975). However, it can be shown that by only the difference between the gravity components in **c**, transformed by some function H, motion sickness can be predicted successfully as it has been observed in a quantitative way (Bos & Bles, 1998). This observer theoretical approach is also applicable more generally, as has been shown by others in addition (Glasauer, 1992; Glasauer & Merfeld, 1997; Merfeld, 1995).
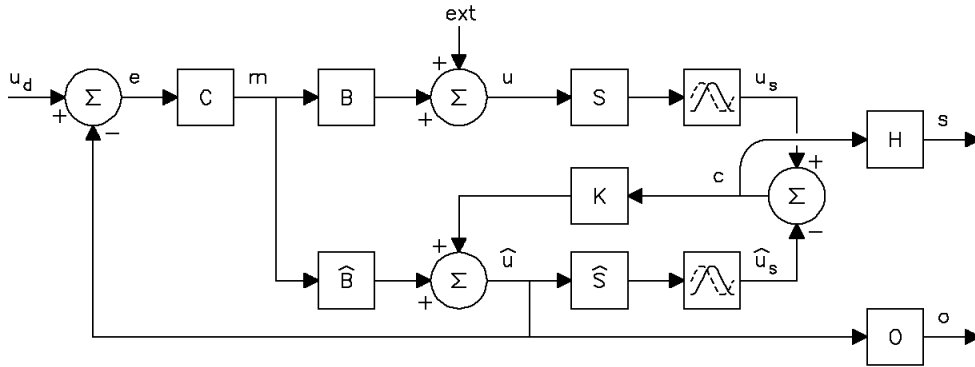
Fig. 1 Spatial orientation and motion sickness model by Bos & Bles (2001; see text for further explanation).

Until now we have elaborated this model for vestibular cues. The key issue then is the specific force resolution problem: How to distinguish accelerations due to motion from the gravitational acceleration. We will here include visual-vestibular interactions so as to be able to predict motion and attitude perception when vision is present, as in a (flight) simulator. Ultimately simulator sickness might be explained as well, but this is not the aim of the present paper. Because we assume that visual and vestibular cues are the most relevant concerning the reflexive subsystems, we will here present an elaboration of the sensor block S in Figure 1. We will focus on intra-vestibular (canal-otolith) and visual-vestibular interactions, therewith

omitting somatosensory ("seat of the pants") and auditory cues, as well as any cognitive interference.

We will also show this model's relevance by predicting, as an example, the perceptions of motion and attitude during a take-off. In simulating a take-off by use of a hexapod or Stewart platform, a short linear forward (x-direction)[1] acceleration, or surge is followed by a slow backward tilting in order to project earth's gravity along the pilot's x-axis (see Fig. 2). However, due to the relatively short translatory range of Stewart platforms, and the fact that the tilting should be realised sub-threshold (regarding the human motion perception system), there is a dip in the resultant forward acceleration profile (see Fig. 3). By means of a simulator experiment and using trained pilots, Groen et al. (2001) have shown which combination of filter parameters leads to an optimum of acceleration, velocity, and attitude perception. There is, however, no explanation at hand why this set of parameters is optimal, and we will conse-quently show how the current model can aid in this respect. To be complete, we also ran these simulations without any actual motion cueing, i.e. as if a fixed base simulator was used.
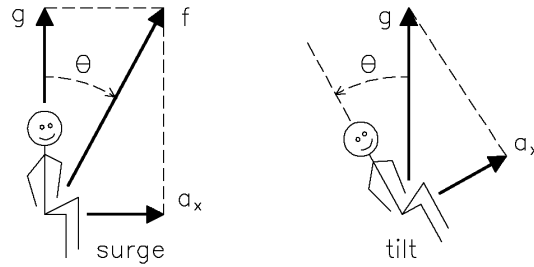
Fig. 2 With a Stewart platform, surge is followed by tilt with the aim to keep the subject refer-enced forward linear acceleration a_x in accordance with some specific profile.
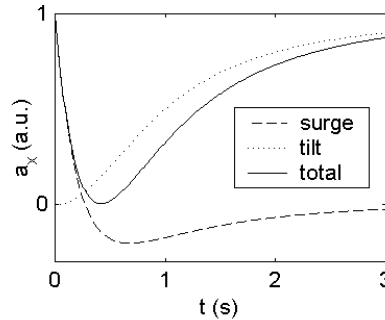
Fig. 3 Sample linear forward acceleration (or specific force, in arbitrary units) generated by a Stewart platform with surge and tilt components.

If the forward linear acceleration needs to be large (i.e. > 1g, and this is particularly relevant in military aviation), a Stewart platform cannot be used. The catapult launch on an aircraft carrier

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[1] We will use a right-handed frame of reference throughout this paper: the x-axis points forward, the y-axis to the left, and the z-axis upward. A positive roll velocity hence results in a tilt to the right, a positive pitch velocity in a tilt forward, and a positive yaw velocity in a rotation towards the left. Because the effect of gravity on our vestibular apparatus is equal to that of an acceleration resulting in a displacement upward, we use a gravity vector that points upward.

is an example of such a condition. Then centrifuges are used instead, applying the centripetal acceleration to mimic a high, possibly longer lasting linear forward acceleration (e.g. Cohen et al., 1973). When a subject is fixed to the end of a centrifuge arm (a distance r from the centre) and he is rapidly brought to a constant angular velocity (ω) about an earth vertical axis, he will experience a centripetal acceleration ($\omega^2 r$) which is perpendicular to the gravitational acceleration (see Fig. 4). The resultant specific force, or gravito-inertial acceleration, hence tilts ramp-wise with respect to the subject. It is observed, however, that the sense of verticality, or subjective vertical (SV) only approaches the direction of the specific force asymptotically within a period of (decades of) seconds. This apparent tilt during centrifugation was termed the somatogravic effect (Graybiel et al., 1947). The relevance of this is indicated by a number of controlled flights into the sea right after nightly catapult launches from aircraft carriers during World War II and the Korean War, just because aviators compensated for the apparent pitch up induced by the high forward linear acceleration (Buley & Spelina, 1970). It is also assumed that every year today a number of mishaps can be attributed to this phenomenon.
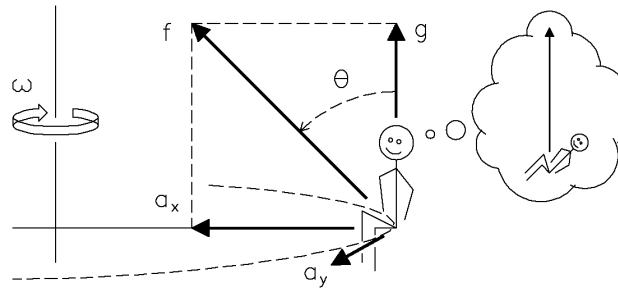
Fig. 4 Human subject facing the centre of rotation (angular velocity ω), experiencing a forward linear centripetal acceleration (a_x), a lateral tangential acceleration (a_y) during on- and offset only, and an upward gravitational acceleration (g), which accelerations add to the specific force (f). As a result of sustained rotation, the subject will feel tilted (approximating θ), which phenomenon is termed the somatogravic effect.
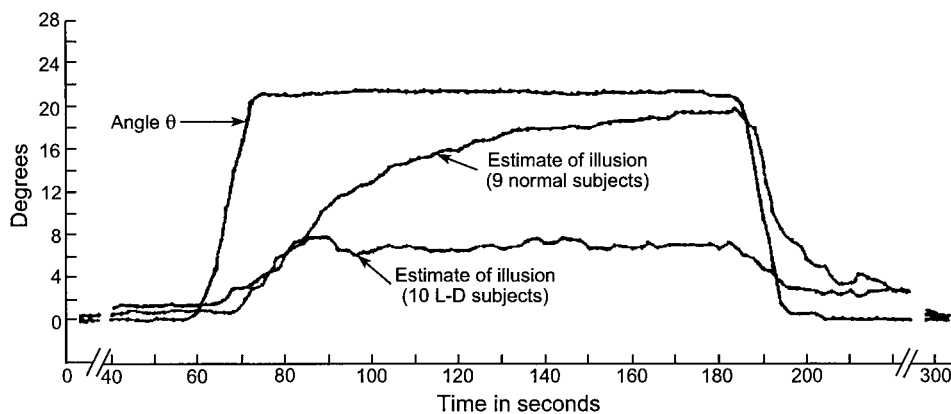
Fig. 5 Average estimated angle of tilt (θ) as observed by 9 normal subjects and 10 labyrinthine defective (L-D subjects), experiencing a centripetal acceleration of approximately 0.4g from t=±60 to t=±185 s (after Graybiel & Clark, 1965).

Figure 5 shows some results of Graybiel & Clark (1965) on both healthy and labyrinthine defective subjects, indicating the significance of the vestibular apparatus regarding this effect.

When elicited by a centrifuge, however, there is a concomitant rotation, and we have recently shown that the time constant of this increase does depend on the angular velocity of the rotation (Bos & Bles, 2001). We will here also reconsider these effects regarding visual-vestibular interactions.

The next three sections will consequently deal with the elaboration of the perception model (block S in Fig. 1). We will show how linear acceleration and velocity, angular velocity, and attitude perception all contribute to human spatial orientation by means of model predictions of hypothetical real and simulated take-offs by use of both a Stewart platform, a fixed base simulator, and a centrifuge. In the general discussion section we will return to the concept of internal models to explain some differences between the model predictions presented here and data as observed.

2 VISUAL-VESTIBULAR INTERACTIONS

The visual system is mainly sensitive to linear and angular position ($\mathbf{x}$ and $\mathbf{\theta}$) and velocity ($\mathbf{v}$ and $\mathbf{\omega}$), whereas the vestibular system senses angular velocity ($\mathbf{\omega}$) and linear acceleration (or specific force, $\mathbf{f}$). However, specific force is composed of accelerations due to motion ($\mathbf{a} = d^2\mathbf{x}/dt^2$) and due to gravity ($\mathbf{g} = \mathbf{F}_g/m$) which accelerations are indistinguishable (Einstein's equivalence principle). To properly control body motion, however, inertial acceleration should be known explicitly, and the specific force resolved by our central nervous system. The subsequent paragraphs will deal with the transfer functions that approximate the basic subsystems first, and how these signals are integrated next to get a perception of linear acceleration and velocity, and angular velocity and position, i.e. attitude.

2.1 Vision

Within our eyes, an image of the outer world is projected onto the retina. In the retina chemical processes generate action potentials that are transduced by nerves to the visual centres within the brain, which centres generate a meaningful output. These processes are relatively slow as compared to the vestibular signals due to the chemical transformation within the retina, complex image processing at the various stages within the visual system, and neural delays. Notwithstanding the complex processes involved, we approximate the input-output relation as follows.

Linear velocity: What we roughly "see" is linear velocity and position (the latter not of interest at present), and we don not "see" acceleration. Though we can "see" differences or changes in velocity, we presently do not take this possibility into account. If an earth stationary subject is viewing a moving scene, he (or she) will generally interpret this as if he moves himself, while the outer scene seems stationary. If the motion is linear the phenomenon is termed linear vection (e.g. we "think" *we* are leaving the platform when in fact the train next to ours is leaving), and vection is obtained within seconds. Here we will assume that the visual scenes we are dealing

with do induce linear vection, and we will use a first order approximation of this process. With $\mathbf{v}_e$ representing the velocity with respect to earth, and $\tau_v = 1$ s, we then have

$$\mathbf{v}_{vis} = \frac{1}{\tau_v s + 1} \mathbf{v}_e .$$

(1)

Angular velocity: If the motion that induces vection is rotatory, the phenomenon is termed circular vection. Circular vection is generally only reached after several seconds of seen motion. Because it is observed that the sense of angular velocity is just given by the opposite of vestibular angular velocity (see below), we take (with $\tau_c = 10$ s)

$$\boldsymbol{\omega}_{vis} = \frac{1}{\tau_c s + 1} \boldsymbol{\omega}_h .$$

(2)

Attitude: What we also "see" is the direction of gravity (although not it's magnitude). Most structures around us are composed of perpendicular lines (frame information), and houses and trees are normally oriented upright (orientation information), whereas the horizon is always horizontal. This is also a relatively fast process for which we use a first order approximation too. With $\tau_v = 1$ s again, we here take

$$\mathbf{g}_{vis} = \frac{1}{\tau_v s + 1} \mathbf{g}_e .$$

(3)

2.2   Vestibulum

Semicircular canals: The vestibular system is composed of the semicircular canals (SCC), a set of three more or less orthogonal canals within each inner ear. Each canal contains fluid (endolymphe) that will lag head rotations due to inertia. Each fluid flow is sensed by some sort of valve (the cupula) with the same density as the endolymphe so as to be insensitive to linear motion. These SCC act as angular acceleration sensors, be it that their output is proportional to angular velocity in the frequency range of naturally made head and body movements (Steinhausen, 1931, 1933; Van Egmond et al., 1949; Groen, 1956, 1957; Robinson, 1977; Raphan et al., 1979). By approximation the transfer function of the SCC may therefore be given, with $\boldsymbol{\omega}_h$ the head angular velocity and $\tau_c = 10$ s, by

$$\boldsymbol{\omega}_{SCC} = \frac{\tau_c s}{\tau_c s + 1} \boldsymbol{\omega}_h .$$

(4)

Otoliths: Within the configuration of these SCC there are also layers of hair cells with crystals (otoliths) on top, with a higher density than the surrounding fluid. These otoliths function as more or less perfect three-dimensional DC-accelerometers (Merfeld et al., 1993). We therefore take the transfer function of these otoliths to be the identity, i.e.

$$\mathbf{f}_{OTO} = \mathbf{f}_h .$$

(5)

2.3   Idiotropic vector

It is known that people tend to align their subjective vertical (SV) in the direction of their own longitudinal body axis (Mittelstaedt, 1983). Though this is evident on earth, it is most striking in space when no gravitational cues are present. Then the SV is often aligned completely with the main body axis. Mittelstaedt proposed the existence of an idiotropic vector to explain this phenomenon. This vector is aligned with the longitudinal body axis, has a relatively small magnitude, and is added to the SV such that the sense of verticality tends to align with the main body axis. We will here use this proposition too.

2.4   Specific force resolution

To move about on earth in a controlled manner, knowledge of self-motion is a prerequisite. Here, also the human CNS has to deal with Einstein's equivalence principle. By path integration we may calculate position from acceleration. If we would then not discern gravity as such, we might feel like an astronaut within five minutes ($\Delta x = \iint g dt^2 = \frac{1}{2}gt^2 \approx 440$ km, with $g = 9.81$ m/s^2 and $\Delta t = 300$ s). The fact that we don't "feel" this indicates that our CNS employs some algorithm to successfully filter out gravity. Mayne (1974) suggested that a simple low-pass filter may describe this CNS-action because gravity is always constant, while (self generated) accelerations are variable. This idea was incited by the somatogravic effect (see above). As described above also, the otoliths respond linearly to the specific force $\mathbf{f} = \mathbf{a} + \mathbf{g}$. Because the otoliths are head fixed while gravity is earth fixed, the acceleration $\mathbf{a}$ needed for proper path integration should hence be calculated by

$$\mathbf{a} = \mathrm{R}_{\omega}\left(\mathbf{f}\right) - \mathbf{g}.$$ **(6)**

Here, the rotation matrix R_{ω} can be obtained by SCC signals, as well as by vision, and we will explain their interaction below. The matrix R_{ω} thus rotates the head-referenced GIA into an earth-referenced vector. In the resulting earth fixed frame of reference, gravity can be estimated by a low-pass filter. Let us denote the perceptions of gravity and motion by $\widetilde{\mathbf{g}}$ and $\widetilde{\mathbf{a}}$ respectively. In Laplace notation we then have

$$\widetilde{\mathbf{g}} = \frac{1}{\tau s + 1}\mathbf{f} \quad \text{and} \quad \widetilde{\mathbf{a}} = \frac{\tau s}{\tau s + 1}\mathbf{f},$$ **(7)**

such that always $\widetilde{\mathbf{a}} + \widetilde{\mathbf{g}} = \mathbf{f}$. Equation 7 implies that the acceleration of self-motion perception is just the counterpart (i.e. a high-pass response) of the sensed vertical, as we have observed indeed (Bos & Bles, 2001). The scheme by which we assume gravity is estimated by our CNS is shown in Figure 6 (after Bles & De Graaf, 1993). Here, otolith signals are rotated first to get an earth-referenced vector, because gravity is only constant in an earth fixed frame of reference. Only then can a low-pass filter estimate gravity. An inverse rotation next gives the head referenced gravity vector as we "feel" it.
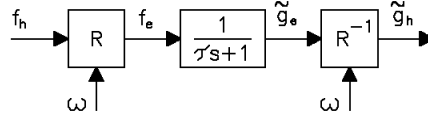
Fig. 6 Functional signal flow from head referenced otolith ($\mathbf{f_h}$) and canal (ω) signals via earth referenced signals ($\mathbf{f_e}$ and $\widetilde{\mathbf{g}}_e$) to the head referenced sensed vertical ($\widetilde{\mathbf{g}}_h$).

We have previously shown (Bos & Bles, 2001) that the mathematical equivalent of this model can be written as a three-dimensional differential equation yielding an estimation of gravity $\widetilde{\mathbf{g}}$

$$\frac{d\widetilde{\mathbf{g}}}{dt} = \frac{1}{\tau}\left(\mathbf{f} - \widetilde{\mathbf{g}}\right) - \omega \times \widetilde{\mathbf{g}} ,\qquad\qquad(8)$$

where we have omitted the head-referencing index "h", Because this equation is the three-dimensional equivalent of a two-dimensional model by Mayne (1974), we previously suggested to call this the Mayne equation. Hence, by (8) the CNS is capable of solving the specific force resolution problem. For the following we take $\tau = 5$ s, conform Bos & Bles (1998), and we will omit the formal notation with a tilde to indicate sensed motion and attitude.

Under natural conditions, i.e. of self propelled (loco)motion, our vestibular system functions adequately: We can control our body motion well (we rarely fall over), we can realise a satisfactory visual fixation, and we do not get motion sick. It is only under artificial conditions like being moved by an aeroplane or ship, or with incongruent vestibular and visual motion like in a simulator, that the system is driven beyond its range of near perfection and troubles with posture, gait, vision, or sickness may occur.

2.5   Visual-vestibular interactions

There are at least three separate levels of visual-vestibular interaction. First, the visual and vestibular angular velocity signals should be combined. Secondly, also visual and vestibular velocity signals should be combined. Third, attitude should be determined by visual, vestibular and idiotropic cues. These three levels of interaction are shown in Figure 7, and this figure may be taken as a guide for the subsequent text.
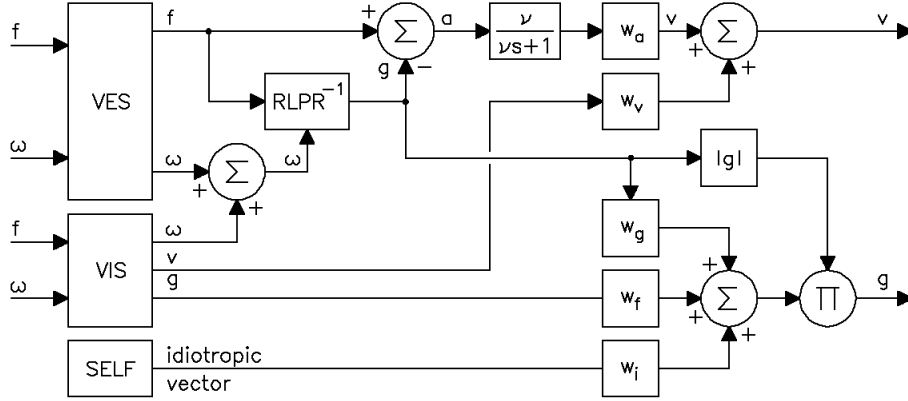
Fig. 7 Resolving linear acceleration (**a**) and velocity (**v**), angular velocity (**ω**), and attitude (**g**) by means of integrated visual (VIS) and vestibular (VES) inputs (**f** and **ω**), together with the idiotropic vector (see text for further explanation).

In Figure 7, otolith output (**f**) is rotated first, filtered and rotated back to get an estimation of gravity as described above (RLPR^{-1} c.f. Fig. 6). Then, linear acceleration and velocity, angular velocity, and attitude are determined as follows. Where appropriate, we will combine inputs (**u**$_i$) when they have the same dimension into one output (**y**) using a linear weighted addition conform Howard (1997)

$$\mathbf{y} = \frac{w_1\mathbf{u}_1 + w_2\mathbf{u}_2 + ... + w_n\mathbf{u}_n}{w_1 + w_2 + ... + w_n} . \tag{9}$$

Linear acceleration: If the gravity estimate from the RLPR^{-1} block in Figure 7 is subtracted from the original otolith signals, we get linear acceleration (**a**) due to motion. Because we do not "see" acceleration, this (apart from somatosensory cues that we have omitted here) is the linear acceleration percept. Moreover, because acceleration and force are linearly dependent (Newton's second law), and force perception is not dependent on vision either, visual signals only enter the path of motion perception after vestibular signals have been integrated temporally.

Linear velocity: If someone is accelerated linearly without visual information (e.g. eyes closed), his perception of acceleration will vanish due to the estimation by means of the high-pass filter conform (7). But, if a vestibular velocity estimate would be calculated by mere integration over time, there still would be a nonzero velocity percept, even if the subjective acceleration has returned to zero. This is in disagreement with observations, and we therefore assume that an additional high-pass filter drives the vestibular velocity percept towards zero. We model the vestibular velocity percept accordingly by

$$\mathbf{v} = \frac{1}{s}\frac{\nu s}{\nu s + 1}\mathbf{a} = \frac{\nu}{\nu s + 1}\mathbf{a} , \tag{10}$$

and hence this is a low-pass filtered acceleration in effect. For the time being we take $\nu = 5$ s. We furthermore assume that visual and vestibular signals are weighted and added linearly conform (9). We here take (see Fig. 7) weights $w_a = 0.2$ and $w_v = 0.8$ supposing a dominance of visual information. This choice has largely been instigated by Groen et al. (2002).

Angular velocity: We already stated that circular vection behaves contrary to vestibular angular motion perception. If both sources of information are present, like when we normally turn our head and both visual and vestibular cues are present, the sense of self motion is (nearly) perfect, just by adding these two sources of information (Eqs 2+4), i.e.

$$\omega = \frac{\tau_c s}{\tau_c s + 1}\omega_h + \frac{1}{\tau_c s + 1}\omega_h = \omega_h \,, \qquad (11)$$

and this is also shown in Figure 8. We therefore add low-pass filtered visual flow-information to canal output to get one signal (ω) that is used in the differential equation (8) conform Figures 6 and 7.
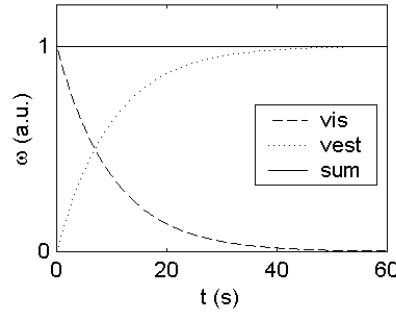

Fig. 8 Visual and vestibular angular signals (here after a unit velocity step) add linearly to a veridical sense of angular motion.

Attitude: Attitude is mainly determined by three factors: visual, vestibular, and idiotropic. These components cannot be added as the linear velocity components, because the attitude vector is determined differently for direction and magnitude. The vestibularly determined gravity vector (8) contains both orientation and magnitude information. The visual and idiotropic vectors on the other hand can only indicate orientation; there is no way for the visual system to estimate the magnitude of gravity. Hence, we propose that the vestibular, visual and idiotropic vectors are all assigned an arbitrary length indicating their mutual weight first and added thereafter, conform (9) again. This is similar to a procedure proposed by Mittelstaedt (1988). But, we next assign the resultant vector indicating the subjective vertical a length as indicated by the vestibular system only (albeit that eventually the somatosensory system may be involved as well). The attitude estimation needs a magnitude for explaining motion sickness, because of the following. The difference between the gravity vector as determined in the primary sensor path and that determined by the internal model from Figure 1 is correlated with motion sickness in general and in the case of flight simulation with simulator sickness in particular. Because the influence of vision on the final estimation of tilt is large and that of the idiotropic vector is small (Mittelstaedt, 1983), we presently set the parameters of Figure 7 to $w_f = 0.75$, $w_i = 0.05$ and $w_g = 0.2$. Without vision $w_f = 0$, and a summary of all weight factors used in this study is listed in Table 1. These choices have been instigated by Groen et al. (2002).

In practice, the SV is often registered just by asking a verbal estimate of self-tilt in degrees, or by setting a joystick. Then attitude is determined by the arctangent of the ratio of the horizontal and vertical components of the gravity estimation. In case of a tilt in the *x-z*-plane the angle of tilt θ is given by

$$\theta = \arctan \frac{g_x}{g_z} \,. \tag{12}$$

Table 1 Motion filter parameters of Groen et al. (2001).

weighting coefficients	flow		frame and orientation		
	w_a	w_v	w_g	w_f	w_i
with vision	0.2	0.8	0.2	0.75	0.05
without vision	1	0	0.95	0	0.05

3   EXAMPLES IN FLIGHT AND FLIGHT SIMULATION: TAKE-OFF

We will now show how the perceptions of linear acceleration and velocity, angular velocity, and attitude according to this model, and to what we know from experienced pilots will change given two types of take-off. First we will show the effects of a moderate take-off common in civil aviation, and this is generally simulated by use of a hexapod or Stewart platform, and also with fixed base simulators. Then we will show a high G-load take-off as common on aircraft carriers during a catapult launch, for example, and this is more of relevance to military aviation.

3.1   Stewart platform

The simulation of a take-off run with a Stewart platform is always hampered by the transition of the specific force along the longitudinal axis from surge acceleration to simulator cabin tilt imposed by the motion range of the platform (see introduction, Figs 2 and 3). To systematically look for those parameters that irrespectively result in an optimal motion perception (i.e. as close to those of a real take-off as possible), Groen et al. (2001) performed a simulator experiment with trained pilots. We will shortly review their findings first, and then calculate the perceptions of motion and attitude under some of these conditions by the model of Figure 7.

Simulator trials: The motion filter used by Groen et al. (2001) is shown in Figure 9. In this figure we also indicate how the accelerations have been recalculated for the present analysis to give the head-referenced components.
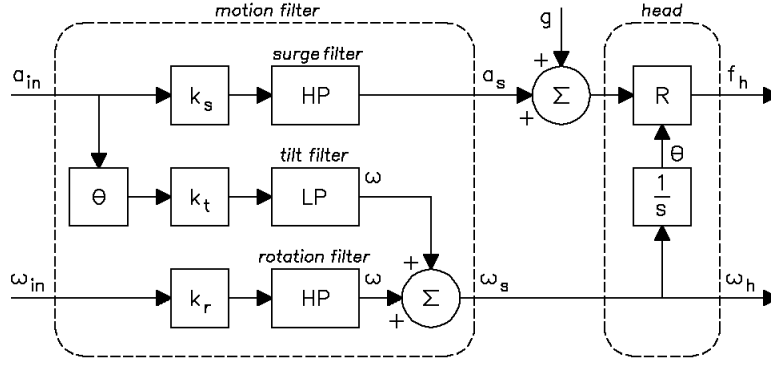
Fig. 9 With a fixed input-acceleration (a_{in}) and angular motion (velocity ω_{in}) simulator acceleration and tilt are determined by the motion filter. The head-part of this scheme determines the motions as sensed by the vestibular system (head).

The applied surge filter here is given by

$$a_s = \frac{s^2}{s^2 + 2\zeta\omega_0 s + \omega_0^2} a_{in},$$ (13)

whereas the tilt filter is given by

$$\omega_s = \frac{k_1}{s^2 + k_2 s + k_3} \omega_{in},$$ (14)

and the rotation filter is inactive because $\omega_{in} = 0$ was set in their experiments. Groen et al. have used a constant acceleration $a_{in} = 0.35g$. Tilt acceleration was limited to $3°/s^2$ and tilt rate was limited to $3°/s$. The parameters $k_1 = k_2 = k_3 = 4$ and $\zeta = 1$ were fixed, whereas the natural frequency ω_0 of the surge filter and the surge and tilt gains k_s and k_t were varied. The horizontal cabin excursion, however, was fixed to 1.5m. The visual used by Groen et al. was a 142° × 110° field of view showing a textured runway moving conform the simulated acceleration. Subjects always had their eyes open. From Groen et al. their data we here took two settings, one resulting in the best performance, the other in the worst performance as judged by their subjects based on force, velocity and attitude perception. Table 2 shows these settings. Figure 10 shows the resultant forward head referenced accelerations. We used $g = 9.81$ m/s^2.

Table 2 Motion filter parameters of Groen et al. (2001).

	good	bad
surge gain k_s	0.2	0.8
tilt gain k_t	0.6	0.4
ω_0	0.726	1.453

Model predictions: In addition to the predicted perceptions of a hypothetical real take-off (a linear acceleration step without any tilt), both the "good" and the "bad" motion profiles have next been used as input to the model of Figure 7, as well as a run with no physical motion at all (fixed base simulator). The visual stimulus always was an earth horizontal accelerated motion (acceleration step) fixed to the subject referenced frame, congruent with the constant accelera- tion of 0.35g. To visualise the effect of vision on motion and attitude perception, we ran four additional simulations with no vision included. Table 3 summarises these conditions.

Table 3 Simulated Stewart platform conditions.

	real	good	bad	fixed base
with vision	a	c	e	g
without vision	b	d	f	h

All responses are mostly characterised by their *x*-component, and we will therefore confine the results to the responses along this longitudinal axis, except attitude, which is defined by (12). Because the only angular motion involved is about the *y*-axis, this will also be the only angular velocity component shown. Figure 10 then shows all results for these conditions, and we will discuss these below. In the subplots showing attitude, the stimulus is also defined according to equation 12, however, with *g* (the gravity estimation) replaced by **f** (the input specific force).
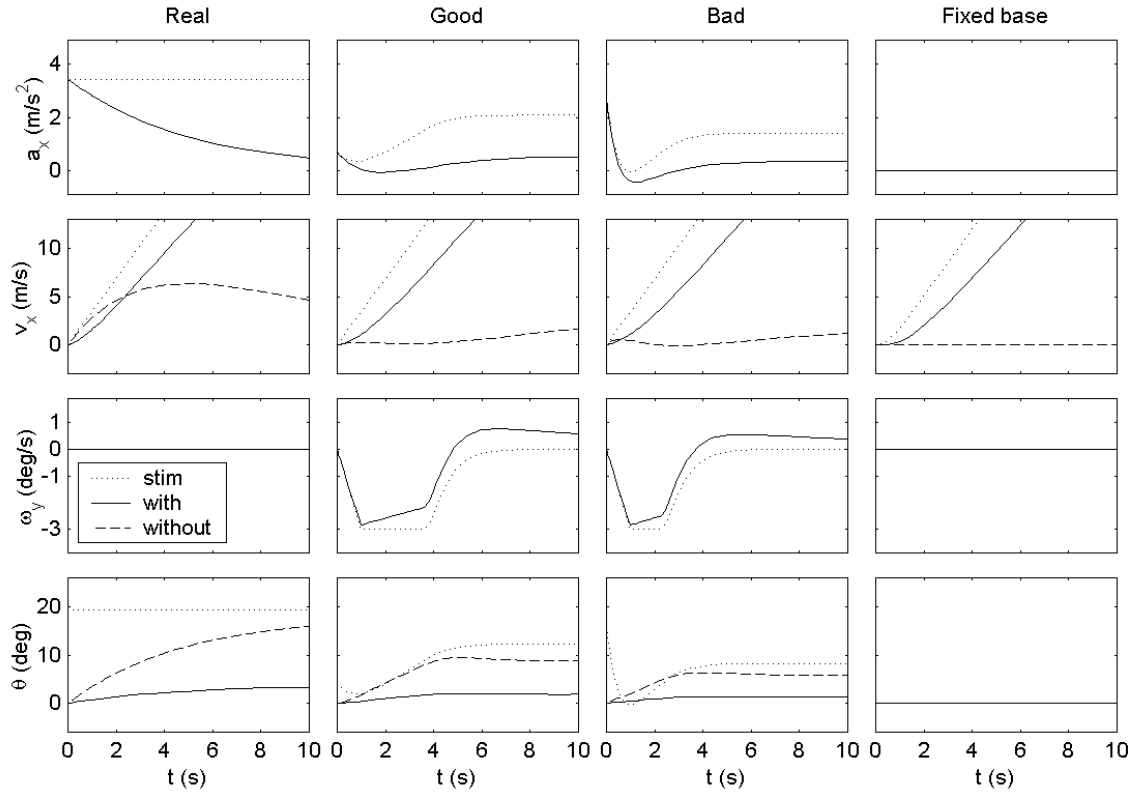

Fig. 10 Model predictions regarding a moderate take-off. Left: results of a real take-off (a+b from Table 3). Second left: results of a simulator run judged to be good (c+d from Table 3). Second right: results of a simulator run judged to be bad (e+f from Table 3). Right: results of a simulation with a fixed base simulator, i.e. only visual flow is present (g+h from Table 3). Shown are the predicted perceptions of acceleration (a_x and stimulus acceleration with dotted lines), linear velocity (v_x), angular velocity (ω_y; note that pitch is the only true rotation involved), and tilt (θ). Results with vision are shown by solid lines, without vision by dashed lines.

Discussion: Because there is no difference between the eyes open and eyes closed conditions regarding acceleration or force, these traces coincide. Apparently, both the good and the bad runs are very dissimilar regarding the acceleration perception from that in the real take-off. Though the bad simulator run shows an initial response that is more close to the response of a real take-off, the subsequent part due to the tilt of the simulator in a good run is more close to the real perception. This especially turns up when visual information is absent (e.g. dark night take-off or bad visibility due to fog). Also the good run does give a perception of acceleration in

the same direction as compared to the perception of a real take-off, whereas that in the bad run is reversed (at $t \approx$ 1s). A fixed base simulator does not generate any perception of acceleration or force.

Due to linear vection, all velocity responses lag the stimulus slightly, and vision dominates the vestibular component in such a way that the good and bad runs look almost equal. Differences appear clearly when there is no visual information available, and then the velocity perception is definitely inadequate. In the fixed base condition, linear velocity is the only component of all motion perception elements that contributes to a sense of motion anyhow, and, accordingly, this sense of motion will vanish completely in bad visibility conditions, despite the fact that there may be an actual motion.

Angular velocity is not influenced by vision because there is no rotatory visual flow present in any of the conditions. Perceived angular velocity, of course, is always below the limit set to 3°/s. We will discuss this further at the end of the paper.

The angle of the subjective vertical shows that the response of a "good" simulator run matches the response of a real take-off more closely on average than that of a bad run. As for the linear velocity perceptions, here also a difference can be observed between the conditions with and without vision. The tilt (i.e. the somatogravic) illusion is suppressed dramatically by vision. The fixed base simulation does not generate any tilt illusion whatsoever.

3.2   Centrifugation

A Stewart platform is insufficient when simulating a take-off with a higher sustained acceleration (i.e. >1g), and this is especially relevant in military aviation. Because long lasting high G-loads can be induced by a centrifuge, this type of stimulation has been used to simulate a catapult launch from an aircraft carrier (e.g. Cohen et al., 1973). When the somatogravic effect (see introduction) is elicited by a centrifuge, however, there is concomitant rotation, definitely supra-threshold, and as mentioned before, this rotation does have a large impact on the somatogravic effect (Bos & Bles, 2001). The effect of concomitant angular motion induced by a centrifuge on motion perception is most clearly demonstrated by means of a pure hypothetical long lasting linear acceleration as will be considered in the next example. However, the high G-load provoked by the catapult launch on aircraft carriers is mainly present during the catapult phase, i.e. during 2-4 seconds only, and we will therefore also consider a run that just ends after a short acceleration profile. Because we already evaluated the effect of missing true motion as in a fixed base simulator, we will leave this out here. We are, however, interested in the effects of vision again, and we therefore ran these conditions with and without congruent linear forward visual flow information. This resulted in eight simulations as listed in Table 4.

Table 4 Simulated centrifuge conditions.

| | real | | centrifuge | |
	long	short	long	short
with vision	i	k	m	o
without vision	j	l	n	p

Model predictions: Here we will consider a subject fixed to the end of a centrifuge arm facing the centre of rotation, at a distance $r = 3$m. The centripetal (forward) linear acceleration then depends on the angular velocity (ω_z) of the centrifuge, and, as opposed to a pure linear forward acceleration, the centripetal acceleration cannot be varied stepwise. We will therefore include a short one second centrifuge onset and offset interval with constant angular acceleration (α_z) in these trials. In fact, centrifuge value is largely determined by this onset rate. The centrifuge motion variables relevant here are then given by

$$
\begin{aligned}
a_x &= \omega_z^2 r & \omega_x &= 0 & v_x &= \int a_x dt \\
a_y &= \alpha_z r & \omega_y &= 0 & v_y &= 0 \\
a_z &= g & \omega_z &= \int \alpha_z dt = \alpha_z \Delta t & v_z &= 0
\end{aligned}
\tag{15}
$$

with a_x the centripetal forward (linear) acceleration, a_y the tangential acceleration, Δt the onset interval, and v the linear velocity of a congruent visual flow field. We choose $a_x = 3g$, such that the final velocity is about 100 m/s ($\cong$ 200 kts).

Fig. 11 Model predictions regarding a long catapult like take-off. Left: results of a real take-off (i+j from Table 4). Right: results of a centrifuge run (m+n from Table 4). Shown are the predicted perceptions of acceleration (a_x and stimulus acceleration with dotted lines), linear velocity (v_x), angular velocity (ω_z; note that yaw is the only true rotation involved), and tilt (θ). Results with vision are shown by solid lines, without vision by dashed lines.

The model parameters are kept equal to those for simulating the Stewart platform conditions. Figure 11 then shows the results, analogous to those of Figure 10 for the long acceleration profiles, and Figure 12 for the short runs. Because the only angular motion involved here is about the *z*-axis, this will also be the only angular velocity component shown here.
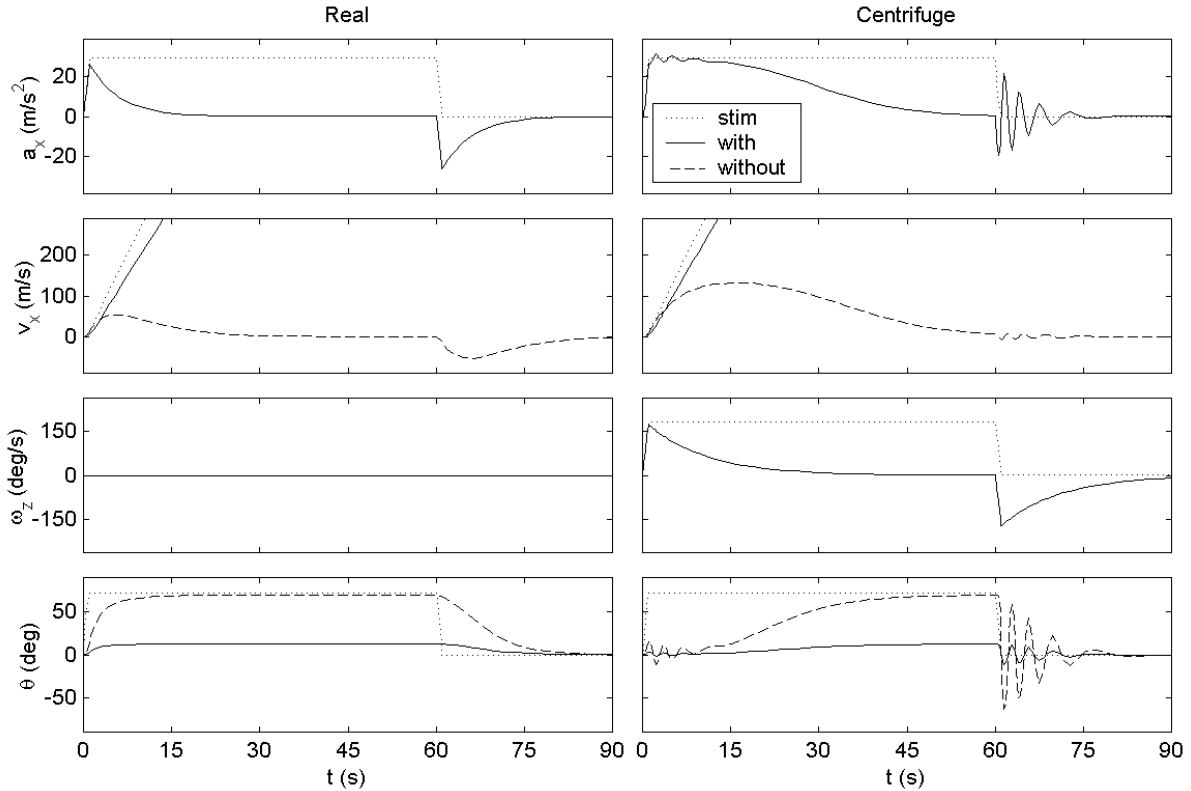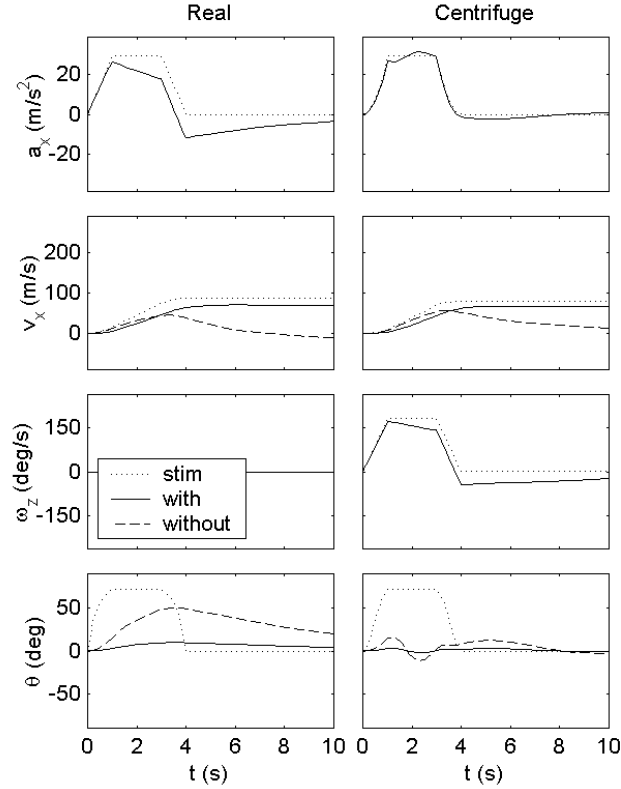

Fig. 12 Model predictions regarding a short catapult like take-off. Left: results of a real take-off (k+l from Table 4). Right: results of a centrifuge run (o+p from Table 4). Shown are the predicted perceptions of acceleration (a_x and stimulus acceleration with dotted lines), linear velocity (v_x), angular velocity (ω_z; note that yaw is the only true rotation involved), and tilt (θ). Results with vision are shown by solid lines, without vision by dashed lines.

Discussion: For known reasons, there again is no difference between acceleration perception with and without vision in both take-off profiles. During the long centrifuge run, the perception of acceleration returns to zero, which takes much longer in the centrifuge. After cessation of the long lasting forward acceleration, this induces a negative acceleration perception in the real run, and an oscillation in the centrifuge run. This is just opposite to the sensation of tilt, and this will be discussed below. In the short run, the acceleration profiles are alike.

The perceptions of linear velocity are, again, dominated by the visual system, and for that reason there is not much difference between the real and centrifuge take-offs. As opposed to the Stewart platform, however, the perception of linear velocity is larger in the long simulator run as compared to that in a real take-off when vision is absent. This is due to the concomitant angular motion. In the short runs, the perceptions of velocity seem to be about equal.

Angular velocity is one of the main problems in simulating a high G-load take-off. Here, the perceived angular velocity is over 180°/s, which is far above the perception threshold of 3°/s.

The angular motion perception is therefore extremely disorienting, and this fact cannot be set aside.

Qualitatively, the model does predict the perception of tilt as it has been observed (see Fig. 5). Note that the curve shown in Figure 5 represents an average, and the oscillations after centrifuge deceleration have probably been cancelled resulting in a large asymmetry. The model also predicts this asymmetry. However, we know now that the perception of tilt is much different in the real situation as compared to a simulated condition. In the long run, after some initial oscillations (which are no model simulation artefacts), the tilt increases much slower as compared to the tilt due to a linear acceleration without concomitant angular motion. We have previously shown the dependency on angular motion (Bos & Bles, 2001). The most dramatic effect, however, and we have observed this in practice (Bos & Bles, 2001), appears at centrifugation offset. Due to the high-pass characteristics of the SCC, there is a strong rotation sensation after motion cessation, and this signal rotates the subjective vertical (see equation 8). The projection of the SV onto the x-z-plane therefore results in the oscillation as observed. Because acceleration perception is the opposite of tilt (see Fig. 7), acceleration perception will also oscillate in this case. When the canals do not get to rest, as is the case in the short centrifuge run, this effect is largely absent. However, also in the short run, tilt perception stays much behind that in a real take-off. A last peculiarity concerns the asymmetrical acceleration/deceleration tilt perception during the long real run. This is explained by the fact that tilt is defined as the arctangent of the x-component divided by the z-component of the final perceived gravity vector, which components are rescaled with respect to the magnitude of the vestibular gravity vector. It is tempting to find out whether this asymmetry can be observed.

4   GENERAL DISCUSSION AND CONCLUSIONS

We described a model for human motion and attitude perception, based on visual and vestibular inputs. One of the reasons for the development of this model was to optimise motion filters used in moving base simulators. The use of this model was demonstrated by focussing on the simulation of a take-off. For moderate accelerations we considered the Stewart and fixed base platforms, for high accelerations a centrifuge. All model simulations were run with and without concomitant visual information such as to elucidate the effects of vision, which is relevant for flying under bad or no visibility conditions. For quantifying the output we used model parameters taken from the literature, except for the weighting coefficients, which were set more or less arbitrarily (though we aimed at expert guesses). Although the results are qualitatively in agreement with observations from the literature, further tuning may prove to be necessary in the future, and we therefore urge for further experiments like those by Groen et al. (2001). For the Stewart platform we here already build on their data where they performed a simulator experiment with trained pilots, and found motion filter parameters that resulted in motions that were judged to be good and other parameters that were judged to be bad. To quantify the perception differences in moving base and fixed base simulators, we also simulated a fixed base simulator, i.e. only linear visual flow was present. Concerning the centrifuge simulations we could also rely on reports by Graybiel & Clark (1965) and Bos & Bles (2001). We hypothesise

that with only a limited number of experiments deliberately set up to determine model parameters, the whole range of flight manoeuvres can be simulated adequately. With the model, insight is given in the different elements of motion and attitude perception that make flight simulation a success or not, and we did find considerable differences between the different simulator modes. We therefore conclude that the presented theory on motion and attitude perception is applicable in optimising motion filters.

Irrespective the fact that not all predictions have been validated yet, some general trends in the data presented here are worth noting specifically, and we will spend the remainder of this discussion to these items. Initially we focussed on spatial orientation, and the presented data show that this cannot be disengaged from motion perception. We therefore considered explicitly four response factors: linear acceleration or force perception, linear velocity perception, angular velocity perception and attitude perception. These may all behave differently because of different visual-vestibular interactions, and these all proved to be high value factors in judging the quality of a simulator manoeuvre.

Linear acceleration: Because force perception is closely related to linear acceleration, and force perception per se is not influenced by vision, we did also not model a visual vestibular interaction in this respect (see Fig. 7). Note that humans cannot estimate acceleration from visual information, and this is yet another reason why we did not take visual information into account at this point. For these reasons there are no differences between the "with" and "without" vision conditions in the perceived linear acceleration traces of Figures 10–12. This also implies that motion perception in a fixed base simulator will always fail due to the absence of this element. On the other hand, thanks to the fact that linear acceleration perception itself is already a high-pass filtered response, acceleration washout is feasible when using a Stewart platform. This is nicely demonstrated by the present data. Most strikingly, both the good and the bad Stewart platform runs are far from the ideal acceleration perception, and this is due to the typical hexapod acceleration dip discussed in the introduction. Though initially a large difference between the acceleration perception can be observed between the good and bad simulator runs, the difference between them is not large at the end. However, despite the continuous positive forward stimulus acceleration there is a negative acceleration perception after one second of motion onset in the bad run due to the high-pass filter. We attribute this reverse acceleration perception to cause the pilots judge this run to be bad, and such a perception should therefore be prevented. In the centrifuge, there is mainly a discrepancy between the perception of acceleration in real and the artificial condition when there is a discontinuity in angular velocity after a longer period of continuous rotation, and this should consequently be avoided too. This, however, is obvious, because it is already known that angular motion, other that that to be simulated, should be kept below the limits of 3°/s and 3°/s^2.

Linear velocity: Linear velocity perception is most clearly dominated by vision, and for that reason the simulator runs with vision seem adequate, independent of the type of simulator or motion filter used. In fact, velocity (both linear and angular) is the only element of spatial orientation that can be controlled when using a fixed base simulator. Hence, when simulating bad visibility while manoeuvring, motion perception will definitely be inadequate in fixed base simulators. When motion is present, the model interestingly predicts that velocity perception is

faster without vision (see Fig. 10, where the dashed line exceeds the solid line during the first two seconds). This is closely related to one of the reasons why we are equipped with a set of motion sensors anyway, i.e. the vestibulo-ocular reflex. Thanks to these vestibularly driven eye movements we can keep visual fixation space fixed, irrespective head movements and the relatively slow image processing by the retina and central nervous system. But, with impeded vision the vestibular response is important, and here, except for the short centrifuge run, the simulator runs are far from adequate.

Angular velocity: In case of the Stewart platform, the angular velocity threshold postpones an adequate gravity projection onto the pilot's *x*-axis (see Figs 2 and 3). Moreover, we would like to stress that the threshold for motion perception is higher than for the oculogyral illusion (Clark & Stewart, 1968, 1969; Miller & Graybiel, 1975). When a subject is rotated below the threshold of 3°/s about an earth vertical axis while looking at a fixation spot that is moving with him or her in an otherwise dark room, this spot may yet appear to move in the direction of the motion. Irrespective the explanation for this illusion, it does indicate that the sensed motion, although not "experienced" as such, does have a firm effect on his visual perception of motion. The threshold limits assumed in flight simulation are therefore by no means absolute. When using a fixed base simulator, circular vection is so slow, that it cannot be used for instantaneous or rapid motions. In case of centrifugation, the angular velocity perception is far above the threshold of 3°/s, and this will counteract any of the other motion and attitude perceptions, and hence frustrate perception realism. Moreover, the angular motion does have a dramatic effect on the somatogravic illusion elicited by centrifugation. We therefore conclude that angular velocity is one of the most annoying factors in flight simulation.

Attitude: Attitude perception predictions are in accordance with the observations known from the literature. As we have demonstrated earlier, the pure somatogravic effect is much faster than assumed before, based on centrifuge data Bos & Bles, 2001; see also Fig. 11). This is due to the concomitant angular motion: the faster the rotation, the more delay. Also the oscillation after centrifuge deceleration is entirely due to the falsely sensed angular motion, and this results in the rotation of the subjective vertical in the process of returning to the upright orientation. If the angular motion has only been constant for a short interval (Fig. 12) then the subjective vertical has not been able to reach its angle of tilt it would have obtained during linear acceleration without a concomitant angular motion. Hence, here also it is the subjective vertical that makes a big difference between perception in true flight and in a simulator. Though differences are present in the Stewart platform simulation and real flight, here the subjective vertical in the good simulation shows to be closer to the predicted perception of a real take-off as compared to the bad run. Also for this reason, fixed base simulation will fail to generate a veridical perception of aircraft motion. By this, and the previous observations concerning the fixed base simulations, we therefore conclude that physical motion adds essential elements to motion and attitude perception that cannot be realised by visual cues only. Furthermore we assume that the subjective vertical explicitly determines motion sickness (Bles et al., 1998; Bos & Bles, 1998, 2001). So this will ultimately give the possibility to optimise motion filters not only with respect to attitude and motion perception, but also for minimising simulator sickness.

The predicted perceptions of linear velocity and attitude differ in a great deal with and without visual information. Figures 10–12 show that visual information, when present, suppresses the vestibular cues dramatically, but not completely. If one argues that it should be suppressed completely, this could be accounted for by implementing a threshold function into the model. However, more elegantly, an internal model as shown in Figure 1 could also account for it. Because the internal model is created by experience, it makes sense that by this experience we have learned that such a condition in fact corresponds with one of no tilt. A last explanation may be that the weighting coefficients w_a, w_v, w_f, w_g, and w_i are no constants, but conditional variables. Which of these "solutions" is the best, or whether yet another solution is applied by our central nervous system remains to be resolved.

Visualisation time delays have not been considered here, because we focussed on the motion of the moving base. However, the model does not exclude the possibility for analysing the results of such delays, and we suggest that also in this respect the model may prove its value.

For generating appropriate linear acceleration within the limits of a ground based simulator facility, centrifugation is the only alternative to tilting as used by Stewart platforms. Moreover, if greater than 1g (rationally > 0.5g) accelerations are to be simulated, centrifugation is the only solution. It has been suggested previously (e.g. Bos & Bles, 2001) for certain manoeuvres to start a centrifuge simulation with the subject in the centre, and keep angular velocity constant from that moment on. First, this situation is maintained until the angular motion perception has returned to zero, and only after this moment the arm length is varied. This, in theory, gives the possibility to vary the level of linear, i.e. centripetal acceleration without the detrimental effects of concomitant angular motion. There are, however, additional problems then, because linear as well as angular Coriolis effects should be taken into account. In theory, these can also be dealt with, and the search for optimal subject motion is one of the major challenges in the (near) future.

Our model does not answer the question completely why subjects as those of Groen et al. (2001) judge the good simulator run to be good, despite the fact that the vestibular stimulus and acceleration perception are much smaller than that of a real take-off. This is in agreement with previous findings concerning motion perception as we observed in a small Friday afternoon trial. There we moved subjects to and fro on a linear sled with and without a helmet mounted display (HMD) that directly showed the image as captured with a video camera mounted on the helmet itself. Here all subjects ($N = 5$) reported that the sled motion was far too strong with the HMD even though it was the "real" motion. In this respect the data of Mesland (1998) are worth mentioning. She also moved subjects on a linear sled to and fro with congruent and incongruent artificial visual motion, and observed that motions were judged to be most natural when considerable phase and amplitude differences were present. One of the reasons why subjects judge simulator trials to be good may be incited by the fact that people rely strongly on velocity and attitude perception and less on acceleration or force perception in their final judgement.

Being of less importance regarding knowledge and rule based behaviour, motion is essential for the pilot's skill based behaviour (Rasmussen, 1983), especially concerning the control of aircraft stabilisation and manoeuvring (Hosman, 1999). Here, subtle differences in motion

perception between real and simulated aircraft motion may give rise to errors in controlling the true aeroplane. As yet, however, there is some controversy about the impact of these errors on actual flying, and transfer of training is the topic of interest. To settle this matter, "transfer of training" should be defined clearly, and experiments covering a wide range of motion profiles and (critical) manoeuvres (like landing) should be realised using different motion platforms. Knowing that one manoeuvre in one typical set-up (motion platform *and* motion filter) does not affect transfer of training, does not necessarily mean that this holds for all types of set-ups. Moreover, it should not be forgotten that motion perception or simulation quality is also highly dependent on the visualisation system used, and this also holds for fixed base simulators. Theoretical analyses of motion and attitude perception as presented here may be helpful in this respect as well. They provide insight in the underlying mechanisms, such as the unravelling of the different perception components, and objectify the differences in perception due to different simulator modes as we have demonstrated clearly.

Irrespective the insights given here and questions raised, the current approach has clearly shown that differences in motion and attitude perception between real and simulated motion in fixed and moving base simulator configurations can be revealed, and these differences are considerable. Moreover, a good run seems to be one in which linear velocity and acceleration, angular velocity, and attitude perceptions are all as close to the perception components of the real motion as possible. These facts speak in advantage of adding (appropriate) physical motion to the visual in flight simulators, especially when used for training skill-based behaviour. The model presented here accordingly offers the applicable solution for optimising the motion filters needed for that purpose, other than the solution of trial and error as applied by the engineer with magic fingers at the switchboard.

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DECLARATION

The contractor, TNO Human Factors, hereby declares that, to the best of its knowledge and belief, the technical data delivered herewith under Contract No. F61775-01-WE077 is complete, accurate, and complies with all requirements of the contract.

DATE: _____

Name and Title of Authorised Official: _____

I certify that there were no subject inventions to declare as defined in FAR 52.227-13, during the performance of this contract.

DATE: _____

Name and Title of Authorised Official: _____